

Gulf of Mexico Hypoxia: Where Are We On the Learning Curve?

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Introduction

The Gulf of Mexico Hypoxia Management Conference brought together, for the first time, a variety of sources of information and expertise on: the characteristics of depleted oxygen conditions (hypoxia) on the continental shelf of the northern Gulf; factors which cause hypoxic conditions to develop and persist; effects on living resources; changes in the delivery of materials by major rivers, particularly nutrients; the sources of nutrients and the opportunities to control them; and similar phenomena in other coastal seas. What have we learned? What do we yet need to know? And, most importantly what does our present understanding indicate could be done—if anything—to reduce undesirable effects of hypoxia in the Gulf?

In my opening address (Boesch, this conference), I identified seven key questions which must be at least partially addressed before public support and political will can be sufficiently marshaled to undertake and effect the controls needed to reduce hypoxia in coastal waters. These questions encompass trends, consequences, causes, sources, restoration potential, feasibility of pollution reduction, and incentives. For the Chesapeake Bay, I reviewed the history and current understanding related to each of these questions. I will use this same framework to summarize—as objectively as I

can—the state of scientific understanding related to Gulf of Mexico hypoxia as supported by presentations and discussions at the Hypoxia Management Conference. Where appropriate, I will compare this history and understanding to that of the Chesapeake. My objective in doing so is to accelerate the learning and to provide a comparative reference for relating scientific knowledge to management action.

Assessment of Present Status of Scientific Understanding

Question 1: Is the hypoxia a natural phenomenon?

It has been offered by some scientists, managers and lay persons that hypoxia in the northern Gulf of Mexico is a natural phenomenon and, therefore, nothing can be done to alleviate the condition. Whether hypoxia is natural is the wrong question. Enormous quantities of nutrients and buoyant, fresh water—the key ingredients necessary for the depletion of dissolved oxygen in bottom waters in an open, shallow region such as the Louisiana-Texas continental shelf—have long been supplied by the Mississippi River and its tributaries. Thus, it is likely that hypoxia did occasionally occur in the region prior to European and even all human settlement. Rather, the more important question is whether

the severity and spatial and temporal extent of hypoxia has increased coincident with human activities.

This question is difficult to answer based on direct measurements because of the limited period of observation and natural variability. At the Management Conference Nancy Rabalais reviewed the historical data concerning the severity and extent of hypoxia in the northern Gulf. Systematic measurements of oxygen conditions over the Louisiana-upper Texas shelf were begun only in 1985. No trend can be inferred by this decade-long record of summer surveys because of the considerable interannual variability in severity, extent and spatial pattern of hypoxia. Annual and more frequent surveys clearly show the strong influence of river flow and wind mixing on the formation and persistence of hypoxia. Years of high river flow resulted in an area of hypoxia (defined as dissolved oxygen concentration < 2 mg/l) as large as 18,200 km² (1995), while during the extreme low-flow year of 1988, a hypoxic zone of only 40 km² was found during the late summer, shelf-wide survey (although a larger area may have been affected earlier in the year). James Hanifen reviewed the records from monitoring of the Louisiana Offshore Oil Port off Grande Isle, which began in 1973, and observed that the percentage of stations experiencing hypoxia was lower in the early 1980s than in the 1990s. Although these and other scattered earlier observations and monitoring in inshore regions clearly show that summer-time hypoxia occurred for at least 10 years prior to the beginning of systematic measurements in 1985, these data provide an insufficient basis for detection of trends.

Nonetheless, several lines of more-or-less indirect evidence presented by Dr. Rabalais suggest that hypoxia has worsened during this century. The most least indirect of these lines of evidence—in that it relates to bottom dissolved oxygen conditions—is the shifts in benthic

foraminifer microfossils preserved in sediments. The length of time that has passed since these sediments were deposited is determined by radioisotopic analysis. At a site in the Mississippi Delta Bight of southeastern Louisiana (a region which had a high incidence of hypoxia during the last decade), a species which is intolerant of low dissolved and was previously a conspicuous element of the microfauna at that site was not found in sediments deposited since 1870 (Rabalais et al. 1996). Another species known to be tolerant of hypoxia became a proportionally more important component of the microfauna during this century, particularly since 1950. The ratio of another hypoxia-tolerant indicator species to a species indicative of well-oxygenated conditions also increased during the 20th century. Similar trends were found at a few other sites in the Mississippi Delta Bight (Sen Gupta et al. 1996).

Evidence of increased deposition of phytoplankton-derived organic matter at these same sites was provided by Dr. Rabalais in the form of measurements of concentrations of biogenic silica in sediments, which show a slow rise during this century, with a more dramatic rise beginning about 1980 (Turner and Rabalais 1994). Because biogenic silica accumulation in sediments has been shown to be a function of the production of diatoms in overlying waters, the above trend may reflect increased delivery of organic matter (and thus increased consumption of oxygen) to the seabed. The trend in biogenic silica accumulation is well correlated with the flux of nitrogen from the Mississippi River into the Gulf. In a separate study in the same area Eadie et al. (1994) found other evidence in the sediment record (carbon isotope ratios in benthic foraminifers and rates of accumulation of carbon and nitrogen) which also reflects increased hypoxia and supply of phytoplankton-derived material since the 1950s.

The available evidence from the sedimentary record in the Mississippi Delta Bight makes a

strong case that the severity, frequency and/or duration of hypoxia has increased during this century, at least in that portion of the Louisiana continental shelf. The coincidence of microfossil changes, increased phytoplankton deposition, and increased nutrient inputs is consistent with a functional explanation linking nutrient enrichment, stimulation of phytoplankton production, and depletion of dissolved oxygen as a result of the degradation of settling plankton. This evidence does not, in itself, demonstrate that the spatial extent of hypoxia has increased during this same time period; the spatial coverage of the cores available for historical analysis is too restricted. However, if the severity, frequency and/or duration of hypoxia in the Mississippi Delta Bight (one of the regions most regularly hypoxic over the past decade) has increased, it is likely that the spatial extent of hypoxia has also increased.

Another factor which must have affected the spatial extent of hypoxia is the progressive increase in flow of the Atchafalaya River since Henry Shreve dredged through a river meander, creating the Old River, and subsequently the log jam at its juncture with the Atchafalaya was breached during the flood of 1863 (McPhee 1989). Successive floods increased the amount of flow down the Atchafalaya until the completion of the Old River Control Structure in 1963 capped and regulated the flow at 30% of the combined flow of the Mississippi-Atchafalaya system. This substantial discharge flows through the Atchafalaya Basin and Bay to debauch onto the broad, shallow continental shelf. The resulting plume remains fully on the continental shelf, while much of the flow through the main Mississippi mouth mixes with open Gulf water and does not contribute to shelf hypoxia. The Atchafalaya discharge causes the stratified water mass and high plankton production associated with the hypoxic zones on the southwestern Louisiana and upper Texas shelf. It is reasonable to conclude that before

this century, at least, hypoxia was uncommon in that region and that increases in flow and nutrient concentrations during the middle decades of the century (1930s-1970s) caused more extensive and severe hypoxia.

In the Chesapeake Bay, systematic measurements of dissolved oxygen have been collected since 1950, yet interpretation of trends in a 30-year record in that physically much simpler system remained a matter of controversy. Action was taken to ameliorate hypoxia before this question was fully resolved. Also, as was the case for Chesapeake Bay, hypoxia of the northern Gulf of Mexico may have begun to occur or worsen with the advent of land-clearing in the watershed. In the Chesapeake, this was evident in the sediment record beginning in the mid-1700's; for the agricultural Midwest this happened about a century later. The heavily agricultural lands of the upper Mississippi, Ohio, and Missouri basins were previously extensive prairies (tallgrass and shortgrass), oak chaparral, and wetlands, which retained sediments and nutrients more effectively than today's landscape.

Question 2. What are the consequences of hypoxia?

The quantitative data on which to estimate the effects of hypoxia on living resources and the ecosystem, in general, are limited. Donald Harper reviewed knowledge of effects on benthic organisms based on sampling of infauna and diver and video observations of benthic and demersal animals. Demersal organisms, including fish, shrimp and swimming crabs, are not observed near the bottom when dissolved oxygen levels fall below 2 mg/l. They may leave the area or move up in the water column; in any case, mass mortalities of these highly motile organisms are seldom observed. Mortalities of larger, non-swimming organisms, begin to be observed when dissolved oxygen concentrations fall below 1.5 mg/l and infaunal organisms emerge from the sediments and lie moribund on

the sediment surface or, in some cases, swim up into the water column when bottom water concentrations fall below 1 mg/l. Under fully anoxic conditions, virtually all benthic animals are eliminated and mats of chemoautotrophic (sulfide-oxidizing) bacteria appear on the sediment surface. In areas annually experiencing sustained hypoxia, benthic communities are not able to fully recover and are limited to a few opportunistic species which colonize the seabed via planktonic larval dispersal during the cooler months.

These observations are very consistent with the world-wide synthesis of knowledge of effects of hypoxia on benthic organisms recently completed by Diaz and Rosenberg (1995) and summarized at the Management Conference by Robert Diaz. Coupling Dr. Harper's observations with this synthesis, it is reasonable to conclude that the productivity and diversity of animal life is reduced in the portions of the Louisiana-Texas shelf which are annually subjected to hypoxic conditions below 1.5 mg/l. What is less certain are the consequences of these effects on benthic organisms on the functioning of the ecosystem and, in particular, on the bottom-feeding fishes and crustaceans which are important to regional fisheries. Although it may seem intuitive that if prey species are eliminated from such a large area of regular hypoxia, the survival and productivity of predators would suffer, there is little direct evidence of this drawn from observations, experiments or quantitative models.

It is particularly important to understand the consequences of shelf hypoxia on the important fishery resources of the region, particularly the effects on penaeid shrimp stocks which both inhabit the bottom waters of the susceptible shallow shelf zone and support the region's most valuable fishery. Even before Gulf of Mexico hypoxia received much attention and systematic monitoring was begun, Renaud (1986) demonstrated that the catch of shrimp and fish in

fishery-independent trawl surveys decreased precipitously when bottom dissolved oxygen concentrations fell below 2 mg/l. This is consistent with the Dr. Harper's visual observations. Roger Zimmerman analyzed the fishery-dependent data of catches reported by shrimpers within statistical reporting zones on the shelf. Relating catch per-unit-effort within each zone to hypoxic zones mapped in Dr. Rabalais' summer surveys produced a coarse relationship. Off Louisiana highest catches were reported in inshore areas not affected by hypoxia rather than in areas with a high percent of hypoxic bottom. However, statistical comparisons are made difficult because catches are also low in deeper areas not affected by hypoxia and shrimping effort (i.e. sampling intensity) probably falls off where there is severe hypoxia. Shrimpers would not expend much effort where the catch is, as found by Renaud, low or nonexistent.

The effects of hypoxia on fishery resources are difficult to comprehend because they seem seldom to result in massive fish kills. Oxygen stressed fish and demersal crustaceans either move laterally or vertically in the water column to seek oxygenated conditions. James Hanifen speculated that this may make them susceptible to predation by pelagic species. He also noted that shrimping activity is often very intense just inshore of hypoxic areas, possibly concentrating on dense aggregations "herded" shoreward by the hypoxic conditions offshore. He noted that during the summer of 1993 offshore winds caused the impingement of hypoxic waters along the shore of the Mississippi Delta Bight resulting in some mortality of fishes and a "jubilee" of large numbers of motile organisms seeking oxygen in shallow waters. Even though hypoxia may produce few "dead bodies" it is probably harmful to fishery resources through increased losses to pelagic predators or human harvesters as well as through loss of habitat and food resources.

Although beneficial effects of hypoxia *per se* on fisheries have not been hypothesized, it has been suggested that on balance increased nutrient inputs from river inflow—the most important stimulus for eutrophication (see Question 3)—into the northern Gulf of Mexico is beneficial in that it increases primary production and the resulting food resources for fishery stocks. The relationship of high fishery productivity to the enriching effects of the Mississippi River has long been known and led Gordon Gunter (19--) to refer to the region as the “fertile fisheries crescent.” Churchill Grimes reviewed the results of studies of the Mississippi River plume and showed that phytoplankton and zooplankton biomass was higher in the frontal region of the plume. Fish larvae tend to be concentrated and larval production was higher in the surface layer of this frontal zone, due both to physical forces and the more abundant food supply. Is there a positive benefit of this enrichment and how does it compare with any negative effects? Grimes’ results do not help much in answering this question for several reasons: they are limited to a small region around the front of plumes; they do not separate out the effects of nutrient enrichment as opposed to physical factors related to the mixing of river and Gulf waters; they deal with only part of the life history of certain fish species; and they do not address the most important fishery resources of the region, e.g. penaeid shrimp.

One potentially significant effect on living resources which has not been investigated to any degree is the mortality of relatively passive larvae entrained in the large volume of hypoxic water that can extend well above the seabed. Might larval recruitment of both estuarine dependent species, such as shrimp, menhaden and sciaenid fishes, and offshore pelagic species be affected? Mr. Hanifen reported that a menhaden plant recently closed, citing offshore hypoxia as a cause of declining harvests, but there is no evidence which, at this point, is even

suggestive of a link between hypoxia and populations of menhaden, which are near-surface pelagics while in the Gulf.

Although the relationship between nutrient supply and primary (plant) production is predictable, the overall relationship between primary and secondary (animal) production in coastal waters is not well known. Based on experience from around the world summarized by Robert Diaz (Diaz and Rosenberg 1995), it appears that whatever positive effect that nutrient enrichment has on fishery resources tends to be reversed when hypoxic conditions become common and negatively affect bottom fish and shellfish. In Japanese waters where good records of fisheries harvests exist, the production of pelagic, plankton-feeding fish may continue to increase with increased nutrient enrichment, but the production of benthic fish falls off precipitously as bottom dissolved conditions decline.

In reflecting on the presentations at the Management Conference as well as on the literature, I find it amazing that the effects of this extensive and severe hypoxia on one of the nation’s most important fishing grounds have been so little studied. While some important questions about these effects clearly need to be addressed as a matter of priority, I note that there was (and still is) a lack of quantification of the impacts of hypoxia on living resources of Chesapeake Bay at the time of the 1987 policy commitment to reduce nutrient loading into that coastal system.

Question 3: Is hypoxia caused by increased nutrient inputs?

As presented under Question 1, there is limited, but convincing, evidence that the severity and persistence of hypoxia has increased in the Mississippi Delta Bight, perhaps beginning in the late 1800s and more markedly since the 1950s. That hypoxia has increased in extent during that time period over the broader Louisiana-Texas shelf has not been shown, but,

as discussed under Question 1, can be reasonably inferred. Eugene Turner examined several alternate hypotheses which could be proposed to explain hypoxia on the Gulf of Mexico shelf, and increases there to. He presented evidence, most of which has been previously published (e.g. Turner and Rabalais 1991), showing a dramatic increase in concentrations of nitrogen and phosphorus in the Mississippi River since about 1960. Interestingly, this increase in nutrients, particularly nitrogen, in the Mississippi was noted earlier by Walsh et al. (1981), who although they did not link it with hypoxia did suggest that it was stimulating increased organic production in the Gulf of Mexico, and by Smith et al. (1987), as part of an analysis of nationwide water quality trends.

In the same presentation, Dr. Turner presented evidence and reasoning to reject the alternative hypotheses for causes of shelf hypoxia: (1) intrusions of deep, oxygen poor water from the deep Gulf; (2) loadings of organic carbon from coastal wetlands; (3) reduction of nutrient trapping by the Mississippi delta distributary system as a result of more channelized flow; and (4) short or long-term climate changes causing fluctuations in river flow. For example, hypoxic water on the shelf has different salinity characteristics and is not physically connected with the deep oxygen minimum layers in the open Gulf (contradicting the first alternative hypothesis) and the organic matter in shelf sediments has a stable-carbon isotope ratio indicating a phytoplankton rather than vascular plant origin (contradicting the second hypothesis). Although, as discussed under Question 6, John Day presented information showing that the deltaic wetlands and estuaries remove nutrients from water flowing through them, he agreed that only a small portion of spring peak loadings could be removed by deltaic wetlands.

Drs. Turner and Rabalais presented other information which related riverine nutrient

sources and stimulation of phytoplankton productivity on the shelf, including patterns of spatial distribution of dissolved nutrients, nutrient concentration ratios in comparison to phytoplankton nutritional requirements (Redfield ratio), and bioassay experiments to determine limiting nutrients. This information provides important insight into the processes by which nutrients contained in the Mississippi and Atchafalaya river discharges are distributed along the Louisiana continental shelf and stimulate phytoplankton production. William Wiseman described the physical processes which result initially in conservative dilution of nutrients, uptake by phytoplankton, and generally westward movement of the enriched water mass in the Louisiana Coastal Current. Decomposition of the organic production not only consumes oxygen below the density discontinuity between the surface (fresher and warmer) and bottom (saltier and cooler) waters, but also remineralizes nutrients. In this matter, riverine nutrients may be recycled many times, adding new “fuel to the fire” of phytoplankton production as the waters gradually move westward. In interpretation of the ratios of concentrations of major nutrients, Dr. Turner concluded that because riverine concentrations of silica have declined over the last half-century, the concentrations of nitrogen, phosphorus and silica are now in rough balance with regard to phytoplankton nutritional requirements, thus sustaining high phytoplankton production rates.

In addition to the evidence from the northern Gulf of Mexico, the linkage between increasing nutrient inputs and hypoxia is lent credence by similar observations elsewhere in the world—including the Chesapeake Bay—as reviewed by Dr. Diaz (Diaz and Rosenberg 1995). Worsening hypoxia coincident with increased nutrient loading has also been observed during the latter 20th century in other relatively open coastal seas such as the Kattegat (between Sweden and Denmark), the central

Baltic Sea, the German Bight of the North Sea, the northern Adriatic Sea, and the northwestern shelf of the Black Sea. This large scale eutrophication effect is different from the periodic hypoxic events related to direct organic loadings of restricted estuaries, such as described by Jonathan Pennock for Mobile Bay.

Question 4: What are the sources of these excess nutrients?

Most of the information summarized above on the hypoxia phenomenon and its relationship with increasing nutrient loadings is not new and has been published in the peer-reviewed scientific literature. Perhaps the most significant advance in understanding achieved by the Conference came from linking upstream sources with downstream changes in nutrient flux and, ultimately, hypoxia.

Ronald Antweiler presented information on the spatial distribution of nutrients in the Mississippi River during surveys conducted during 1991-92. Transport of inorganic nitrogen and phosphate (estimated by multiplying concentration by flow rate) increases monotonically from the headwaters of the upper Mississippi downstream at least to the confluence of the Arkansas River, indicating that until that point the introduction of nutrients in each segment of the river is greater than their removal (via phytoplankton uptake, sedimentation in reservoirs and navigation pools, and loss of N to the atmosphere as a result of denitrification). A disproportionately large proportion of the nitrate (the primary form of inorganic N) flux comes from the Upper Mississippi River (Illinois, Iowa, Minnesota, and Wisconsin): 51% of the nitrate versus 22% of the water discharge. Similarly, the Illinois River provides 12% of the nitrate and only 4 % of the water discharge (Antweiler et al. 1995).

Richard Alexander presented results of an empirical model of nutrient flux based on water quality monitoring data. The model attempts to quantify the importance of various sources of

nutrients by estimating loadings, watershed physical characteristics and decay of nutrients during transport. Although many factors related to sources and environmental factors such as precipitation, soil permeability, basin slope, and decay have significant effects on the model's predictions, the model performs well when compared with direct observations. Dr. Alexander presented estimates of the contributions of upstream sources to the nutrient fluxes into the Gulf of Mexico. For total nitrogen, 31% comes from the Upper Mississippi, 23% from the Lower Mississippi, 22% from the Ohio River, and 11% from the Missouri River. These ratios differ somewhat from those presented by Dr. Antweiler in part because they reflect contributions to flux into the Gulf (incorporating decay in transit) and not to flux through the river. Thus, Dr. Alexander's estimates of the importance of upper basin sources are lower and of lower basin are higher than those of Dr. Antweiler. By either estimate, however, these results suggest that at least 70 % of the nitrogen which ultimately reaches the Gulf has entered the river system by the time the Ohio joins that river at Cairo (15,000 km) upstream of the river mouth. In contrast, the Lower and Central Mississippi is more important in terms of flux of total phosphorus, however upstream sources are more important in terms of dissolved phosphorus. By analyzing the effect of human population centers on nutrient flux, as reflected in the monitoring data, Dr. Alexander concluded that municipal and industrial point sources probably contribute only about 1 % of the nitrogen loadings to the Gulf; while nonpoint source, including application of fertilizer and manure and atmospheric deposition, contribute 90%.

Donald Goolsby presented additional results from the U.S. Geological Survey's water chemistry monitoring to examine the effect of episodic events on the transport of nutrients to the Gulf of Mexico and to decipher the longer-

term trends in these data. Seasonal and interannual variation in nitrogen flux appears to be a function of climatic variation and hydrological dynamics (including precipitation, runoff, and groundwater storage) and seasonal application and longer-term trends in use of fertilizers. Nitrogen may be stored in groundwater during relatively dry periods and pumped from this storage during higher flow. The concentration and flux of nitrate in water discharged to the Gulf (as measured at St. Francisville and Baton Rouge, Louisiana) increased about threefold between 1954 and the early 1980s. Drought in late 1980s resulted in a decrease in nitrate concentration and flux. An increase in the early 1990s could have been a result of leaching from storage during higher flows. Fluxes have declined since the flood year of 1993. These observations are consistent with the previously published results (e.g. Turner and Rabalais 1991) reviewed by Dr. Turner. As did Dr. Turner, Dr. Goolsby related the increase in nitrate concentration prior to the early 1980s and subsequent leveling off to fertilizer use, which he suggested had increased by four-fold. Both Drs. Goolsby and Turner found that the concentration and flux of total phosphorus has changed little since 1973, when the first records were collected.

Dee Lurry described a study the U.S. Geological Survey was beginning to analyze in more detail data from 41 National Stream Quality Accounting Network (NASQAN) gaging stations in the Mississippi River and its major tributaries. Annual mean concentrations and loads of total nitrogen and total phosphorus will be computed and trends statistically tested.

Several scientists participating in the conference addressed the various sources of nutrients and the cause of the documented increases in nitrogen flux to the Gulf. As mentioned earlier, Dr. Alexander's flux model indicates that point sources from municipal and industrial discharges contribute very little, rather

nonpoint sources dominate. Dr. Goolsby presented a somewhat higher estimate for municipal and industrial wastes (6%), but this is still a small contribution. He estimated the total input of nitrogen into the Mississippi watershed as approximately 11 million metric tons per year, of which 56% is in the form of fertilizer, 25% as animal manure, 9 % as residual from legume crops that fix nitrogen from the atmosphere, and 4% from atmospheric deposition. He indicated that phosphorus inputs are largely agricultural, with 46% from fertilizer and 50% from animal manure. Approximately 60 to 70% of the fertilizer inputs are incorporated into crops. A portion of this is double-counted in his nitrogen budget because some crops (containing nitrogen of fertilizer origin) are fed to animals which produce the manure.

Although it is clear that point sources of N are relatively unimportant, Scott Dinnel presented an analysis which suggested that atmospheric deposition may be more important than Dr. Goolsby indicated. He analyzed data from national monitoring of wet and dry deposition of nitrogen and estimated that the atmospheric deposition—largely derived from nitrous oxides generated by fossil fuel combustion—on the Mississippi drainage basin exceeds the riverine nitrogen flux to the Gulf. While a sizable part of this deposition, particularly that falling on forests, is retained on the landscape, this would suggest that the atmospheric sources, which of course also grew since the 1950s, may also be a significant contributor to eutrophication in the Gulf of Mexico. Dr. Alexander's model does not distinguish among nonpoint sources, but his results and the riverine flux data presented by Dr. Antweiler suggest that atmospheric sources, which are particularly concentrated in the Ohio River drainage, are considerably less important than agricultural sources, which are more concentrated in the Upper Mississippi and Illinois river drainage. By comparison, the

importance of atmospheric deposition of nitrogen to increased nutrient loading to the Chesapeake Bay has also been a matter of controversy and has still not been adequately resolved.

The Management Conference brought together this new information about sources, unambiguous evidence of increased nitrogen flux, and strong inference that the increase in nitrogen loadings had increased the severity and very probably the extent of hypoxia. However, there remained some skepticism among representatives of agricultural and upriver interests attending the Conference. In part, this is because it is difficult to believe that an effect may be so far removed from the cause. And, in part, this is because one's receptivity to such an explanation is affected by the degree to which one experiences the consequences or may be asked to bear the costs of the solution. The connection of cause and consequence may be more believable and solutions more acceptable if it were 500 km of the Mississippi below Cairo, rather than a 500 km broad zone of the Gulf of Mexico, 1500 km away, which was seriously depleted of oxygen!

Although skepticism and even denial of the importance of nonpoint sources existed for the Chesapeake Bay, at least the responsible states were on the Bay, or in the case of Pennsylvania, close by. Still, the difficult connection with remote sources of pollutants remains a problem in the Chesapeake. For example, a recent *Washington Post* news article addressing the need to control atmospheric emissions of nitrogen outside of the Chesapeake watershed (Shields, 1996), reported: "Ohio officials said that any such pressure would be premature and called for more research." A lawyer representing utilities in the Midwest said "he doubted that computer modeling could reliably demonstrate a link between Midwestern emissions and East Coast water pollution."

Question 5: What will be the effect of reducing these nutrients inputs?

Will controls of the sources of nutrients in the Mississippi drainage result in reduction of hypoxia in the Gulf of Mexico? What will be the effects on living resources? These are challenging questions, particularly when the conditions, both in terms of oxygen distribution and fishery productivity, prior to the increase in nutrient loadings are not well known. Victor Bierman prepared a review of his computer model relating nutrient inputs, primary productivity and dissolved oxygen on the Louisiana. The 21-segment model includes salinity, phytoplankton carbon, phosphorus, nitrogen, dissolved oxygen and carbonaceous biological oxygen demand as state variables (Bierman et al. 1994) and was run to simulate the response of the system to nutrient load reductions. The model predicts that reduction of nitrogen loading by as little as 10% would affect the average dissolved oxygen concentration. Using 1985 conditions, the model showed that nitrogen reductions of 50% could increase average dissolved oxygen concentrations by 50 %, while a similar reduction run with 1990 conditions showed that 50 % reductions could increase average dissolved oxygen by 150%. While Dr. Bierman's model is coarse at this time, particularly in comparison to the three-dimensional water quality model presently used to address similar questions for the Chesapeake Bay, it does suggest that significant reductions in hypoxia would result from nutrient source reductions in the range of feasibility. But it is appreciated that in comparison with the Chesapeake, modeling the response of the Louisiana shelf is much more difficult because of the open nature of the system and greater influence of boundary conditions and forcing.

Rabalais et al. (1996) have also attempted qualitative predictions of the effects of future changes in nitrogen loadings. They suggested that hypoxia may increase even if nitrogen

loading remains constant. If silica loadings continue to rebound from a decline in the 1960s and 1970s the relaxation of silica limitation may stimulate phytoplankton production nitrogen loading again begins to increase, the severity of hypoxia would worsen even more. However, if nitrogen loading is reduced, nitrogen would be the more consistently limiting nutrient and hypoxia would decrease.

Of course, specific future conditions will be influenced by short-term and long-term climatic variations as well as nutrient emissions and control strategies. The seasonal and annual variations in freshwater discharges have now been shown to have a dramatic effect on the distribution and severity of hypoxia. Coastal meteorological conditions also influence the distribution of freshwater and mixing, thus stratification and nutrient recycling, thus hypoxia. On a longer term, Justif et al. (in press) suggest that if freshwater discharge from the Mississippi River system increases by 20%, as predicted by some climate change models under doubling of atmospheric CO₂, a significant worsening of hypoxia would result.

Question 6: How can the sources of nutrients be feasibly reduced?

Reductions in nutrient loading to the Gulf of Mexico can be addressed at the source or enhancing nutrient removal via management of flow in the river system. Taking the latter approach first, river engineering which slows flow and increases residence time such as reservoirs, navigation pools, and wide flood plains promote nutrient removal via sedimentation and denitrification. For example, Terry Whitledge (who was unable to attend the conference) reported significant depletion of dissolved nitrogen in a navigation pool in the Upper Mississippi River during the summer. In the Mississippi Deltaic Plain, considerable attention is being given to diversions of river flow into the surrounding wetlands and estuaries in order to restore wetlands and the distributary

functions of the delta. John Day presented several examples of the effectiveness nutrient removal by wooded swamps, estuarine marshes and shallow estuarine waters in the deltaic plain and indicated the beneficial effects of diversion of nutrient-rich waters into these ecosystems. However, it is clear from the maximum effective removal rates (for wetlands 40 g nitrate/m²/yr) that wetland/estuarine diversion would not result in very significant nutrient removal during high river-flow periods. In addition, Eugene Turner raised concerns about the effects of nutrient enrichment on water quality in the estuaries.

While the justification of river diversions in the Mississippi Deltaic Plain lies primarily in their benefits to wetlands and estuaries rather than in reducing nutrient loadings to the Gulf of Mexico, these diversions may nonetheless have significant effects on shelf hypoxia. This is because diversions influence the location of the introduction of nutrient-rich freshwater on the shelf, which in turn affects dilution, stratification and residence time. For example, among the diversions under consideration is the abandonment of the familiar “birds foot” delta and redirection of most of the flow of the Mississippi River to the east into Breton Sound. This would greatly reduce the fresh water entering the Mississippi Delta Bight, the site of regular and severe hypoxia, and greatly increase effluence onto the shelf region off the Chandeleur Islands, an area not presently characterized by hypoxia. The effects of diversion proposals on the offshore environments have, at this point, not been assessed at all.

Returning to the issue of source control, it is clear from the discussion of Question 4 that source reductions must focus primarily on agricultural nonpoint sources. John Burt discussed some of the recent advances in agricultural practices to reduce nonpoint nutrient sources. A wide array of approaches exists including reduced tillage and soil conservation

practices; optimal application of nutrients using new technology (e.g spatial matching of soil requirements and application rates using Global Positioning System technology); cover crops to reduce losses of nitrogen to groundwater; manure application and management; and stream buffers, created wetlands, conservation set asides and other landscape approaches (National Research Council 1993). All of these approaches are being pursued in the agricultural regions of the Chesapeake watershed under voluntary programs promoted by the participating states. Although the jury is still out, it appears that those states will fall well short of reaching the agricultural nonpoint source reduction portions of the 40% reduction goals by the year 2000. Nitrogen controls present a major challenge for agriculture in the Chesapeake watershed and quite likely in the Mississippi basin because nitrogen is highly soluble and much of it is lost from fields via ground water rather than surface runoff. Conventional management practices oriented toward soil conservation, although they are relatively effective for controlling loss of phosphorous, are, therefore, relatively ineffective for controlling nitrogen losses. Furthermore, the nitrogen may reside for months to years in ground water before it enters surface waters, thus causing a lag between source control and improvement in surface water quality. On the other hand, Clive Walker presented results from modeling of soil losses from agricultural lands which suggest that there may be significant losses of organic nitrogen associated with soil erosion.

Where should nutrient source control efforts be focused for maximum effect in reducing loadings to the Gulf of Mexico. The source estimates made by Ronald Antweiler and Richard Alexander suggest that the Corn Belt region of the Upper Mississippi and Illinois drainage must be targeted. However, Dr. Alexander pointed out that on a per-unit-area

basis the contribution to nonpoint-source nitrogen loading to the Gulf was actually higher in the Lower and Central Mississippi drainage. Thus, a greater effect on ultimate loadings would be achieved per acre of farmland placed under improved nutrient management practices in the lower regions. Thus, the farmland of the Lower and Central Mississippi should also be targeted.

As opposed to the Chesapeake watershed, where municipal point sources are also large contributors to nutrient loadings, upgrading sewage treatment by inclusion of biological nutrient removal, although it may produce beneficial effects to water quality locally, would do little to reduce nitrogen loadings to the Gulf of Mexico. As was addressed under Question 4, the importance of atmospheric deposition of nitrogen is more uncertain. Attempts to reduce atmospheric sources in the Chesapeake watershed are just beginning, but it is clear that they must be linked with efforts to reduce ground level ozone.

Question 7: What are the incentives for reducing these sources of nutrients?

Incentives for action to reduce nutrient loadings may be related to: regulatory requirements (and the avoidance of penalties); intergovernmental commitments made under regional compacts, such as the Chesapeake Bay Agreement; financial assistance; or the benefits of waste reduction to the party responsible for generating the waste. Melissa Samet reviewed the background of the 1995 petition to the EPA Administrator and Louisiana officials by the Sierra Club Legal Defense Fund on behalf of 18 other organizations which requested a conference under Section 319 of the Clean Water Act. This section of the statute empowers EPA take steps to reduce water pollution which crosses state boundaries, including convening the responsible and affected states to find solutions and, ultimately, regulatory action. Ms. Samet stated the view of the petitioners that the so-called Dead Zone in

the Gulf of Mexico is indeed a significant problem resulting from interstate water pollution and that enough scientific understanding has been developed to support the need for action. William Kucharski, then Louisiana's Secretary of Environmental Quality, expressed the concerns of the main state experiencing the effects of hypoxia, but also viewed the matter from the perspective of an environmental agency head who has to deal with the political, social and economic realities of decisionmaking. He was troubled by the yet unknown aspects of the problem and cautioned that we can be scientifically correct, but politically wrong in seeking solutions. He preferred a collective approach to solve the hypoxia problem and reported on his efforts to engage the states in the watershed to come to grips with the problem.

Robert Whelan reviewed EPA's efforts throughout the nation in working with the states and citizens to manage ecosystems on a large scale. He pointed out that control of nonpoint sources of nutrients plays an important part of many of these programs, including the National Estuary Program, the Great Lakes Program and Chesapeake Bay Program. He offered that even though the Gulf hypoxia is a problem of daunting proportions, others are dealing with similar problems with some success. Frederick Kopfler provided an overview of the over 200 watershed-based projects in the Mississippi drainage. The goals of these vary, but many include control of nutrients, pesticides and soil erosion. He indicated that success depends on flexibility in financial and technical assistance and tailoring of approaches to match the type and source of pollutants, agricultural practices and community attitudes. Charles Spooner reviewed the efforts to control nutrient pollution of surface and ground water in the Mississippi Basin. Most are directed toward controlling phosphorous, the most important limiting nutrient in freshwater ecosystems. Concerns about nitrogen tend to be restricted to where

there is a risk of nitrate toxicity to humans in groundwater or toxicity of ammonia to fish. He emphasized that the levels of nitrate causing eutrophication are far below those that pose human health problems, thus controls introduced to satisfy drinking water requirements may be insufficient to ensure water quality for living resources. Dugan Sabins reviewed the various efforts underway in Louisiana to control both point and nonpoint sources of nutrients. He described several nonpoint source control program for locally degraded water bodies that, although they would have no effect on hypoxia in the Gulf, indicate to the upriver states that Louisiana is exercising good stewardship.

Byron Griffith, Acting Director of the Gulf of Mexico Program, announced that it was EPA's intention to use the Gulf of Mexico Program as the primary structure to address the understanding and management of Gulf of Mexico hypoxia. This means that upriver states must be engaged, in addition to the five coastal states already participating in the Gulf of Mexico Program. Discussion during the Conference focused on whether the consultative approach would be effective and whether the Gulf of Mexico Program was adequately positioned to involve the non-coastal states upriver. It is clear that increased awareness of the connections between nonpoint sources upriver and their consequences to the living resources in the Gulf need to be made in order to engage the upriver states and agricultural interests in finding solutions.

John Burt provided some perspectives from the agriculture, important because of the dominance of agricultural nonpoint sources in the Mississippi watershed. He stressed the need for more information about the causes of hypoxia, particularly the effects of variable runoff (e.g. floods) as opposed to nutrient enrichment in causing hypoxia, before a "full court press" on agricultural source reduction. He also indicated the need to identify feasible

and effective control levels. He pointed out that conservation programs under the 1985 and 1990 Farm Acts have succeeded in reducing erosion and preserving wetlands, thus reducing nonpoint source pollution. He suggested that these programs be used as part of any future effort to control nonpoint sources of nutrients. He also highlighted the rapid technological advances, such as “precision agriculture,” that allow farmers to reduce nutrient losses while reducing their costs of production. Mr. Burt also indicated that there is pressure to increase agricultural production in the Mississippi Basin in order to meet the growing world demand for grain. Since the Conference the 1996 Freedom to Farm Act has been signed into law. Its implications for nonpoint sources of nutrients entering the Gulf of Mexico are unclear at this time. On one hand, it authorizes additional programs and provides funding to address agricultural nonpoint sources. On the other hand, it eliminates federal market-support programs which compensate farmers for taking land out of production. The soaring price of grain on the world market, driven mainly by Asian import requirements, may result in an increase both in the amount of land in production and the intensity of production, and thus in fertilizer application in the Mississippi drainage.

Conclusion

The Management Conference brought together a wide range of information concerning the causes, consequences and possible solutions for hypoxia in the Gulf of Mexico which, in my opinion, supports the following conclusions:

1. Although varying as a function of freshwater discharge and climatic conditions, hypoxia on the continental shelf of the Gulf of Mexico has increased in severity and, very probably, in extent due to human activities.
2. The primary cause for worsening hypoxia during the last half of the 20th century is a dramatic increase in the discharge of dissolved forms of nitrogen.
3. This increased loading results mainly from agricultural activities (particularly the application of fertilizer and generation of animal wastes), particularly in the northern Upper Mississippi-Illinois basin.
4. The effects of hypoxia on fishery resources and health of the shelf ecosystem are poorly quantified, but the large-scale loss of benthic habitat and prey mortalities that result probably have significant negative consequences to demersal fish and crustacean resources.
5. The level of understanding of the causes and consequences of Gulf of Mexico hypoxia equals or exceeds that which existed at the initiation of other programs which are attempting to control watershed-scale nutrient inputs, such as the Chesapeake Bay Program. The potential effects on living resources are greater.
6. Reduction in the extent and severity of hypoxia is feasible, although the degree of reduction potentially achievable is yet poorly known. Nonpoint source control of nutrients (particularly nitrogen) on a watershed scale will be required to accomplish these reductions. These efforts would have to focus primarily on agriculture, although the possible effectiveness of reductions in atmospheric deposition should also be explored.
7. Possible effects on hypoxia should be an explicit consideration of all engineering activities which affect the flow of water in the Mississippi Basin, including navigation projects, reservoir construction, flood plain management, and river diversions for maintaining delta wetlands.
8. In order to “manage” hypoxia in the Gulf of Mexico, some form of interstate-federal agreement and a concerted program to implement it will be required. However,

because of the vast area and large number of states involved, the federal government must provide strong leadership through its programs of technical and financial assistance and regulations.

9. A key technical requirement is the development of a management-oriented process model (or models) of the input, loss, and transport of nutrients in the river system linked with a integrated oceanographic-ecosystem model of nutrient, oxygen and living resource dynamics. This model should be used to guide strategic research needed to improve understanding and predictions. While other critical research needs will thus be identified, it is clear that research on the effects on living marine resources, groundwater hydrology, atmospheric deposition, and the effectiveness of nonpoint source controls are of high priority. Continued monitoring of continental shelf hypoxia and associated environmental data and riverine fluxes of nutrients is also essential.

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